



# Comprehensive review on enzymatic polymer degradation: A sustainable solution for plastics

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## ABSTRACT

Synthetic plastics have been present in ecosystems for decades, and the increasing usage of plastic polymers has been a serious environmental challenge. The enzymatic polymer biodegradation, catalyzed by microbes, can address this issue by metabolizing the carbon from the polymer chain and decomposing it into simpler constituents. The key enzymes include hydrolase, lipase, cutinase, and peroxidase produced by diverse microorganisms and are responsible for the biodegradation of polymers. The present review has focused on several techniques of polymer biodegradation facilitated by enzymes through specific modes of action. The impact of enzymatic biodegradation of polymers on environmental sustainability has been thoroughly examined. This involves the microorganisms like fungi and bacteria, which utilize the substrate and depolymerize it. Microorganisms, such as bacterial species *Pseudomonas*, *Bacillus*, and *Ideonella*, release various enzymes. Fungal species, specifically *Pseudozyma*, *Candida*, *Fusarium*, *Aspergillus*, *Penicillium*, *Rhizopus*, and the composite microorganisms involved in the biodegradation of polymers, have been studied extensively. Plastic deterioration occurs through aerobic and anaerobic processes, depending on the oxygen presence or oxygen absence conditions. The aerobic process operates efficiently and achieves total breakdown more rapidly than the anaerobic process. Aerobic degradation generates biogas, a renewable energy source, whereas anaerobic degradation creates methane-like gases, causing environmental issues. Oxidation and hydrolysis are the two reaction types involved in plastic biodegradation. The current investigation examines various plastics, including polyethylene, polyurethane, polyethylene terephthalate, polystyrene, polypropylene, and polyvinyl chloride, and their biodegradation mechanisms facilitated by different enzymes.

## 1. Introduction

In the modern era, plastics have diverse applications in society. Plastics have many benefits in our daily lives. It is a packaging material in industries such as medicine, electronics, household things, etc. Due to population growth, economic development, demand for goods, and changes in lifestyle, demand and production are increasing significantly. Plastics are lightweight housing that is flexible, low-cost, and readily available in mass production (Nanda et al., 2022). On the contrary, the indispensable waste dumping of human behaviour is a significant societal issue. The high amount of usage and, thus, dumping and

incineration of plastic pollution affect the environmental impact of a change in global warming and hence will cause health problems [1]. The proper usage and recycling of plastics make an efficient remedy for this. Directly spraying the plastic-degrading microbes or releasing enzymes onto plastics in the environment is challenging. However, the biodegradation of plastic waste into monomers by enzymes, followed by microbial upcycling into value-added chemicals under controlled circumstances, is possible [2]. In order to do this, bioplastics can mitigate environmental and societal toxicity issues. Bioplastics such as starch and cellulose are naturally produced from sugarcane and corn. They can easily be naturally degradable materials as compared to

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synthetic plastics. So, using bioplastics makes another solution to reduce plastic pollution [3]. Biobased and biodegradable plastics, such as PLA, PBAT, and PBS, are promoted as eco-friendly alternatives to conventional plastics. However, they may not be readily biodegradable in natural environments [2].

Microorganisms that are overlooked or underestimated are essential for shaping and maintaining the delicate balance of ecosystems. They are a rich source of novel enzymes (Mytand et al., 2023). These microbial products need the development of various therapeutic agents, including vaccines, anticancer drugs, antibiotics, and therapeutic enzymes [4]. Plastics can be categorized into two main classes: non-biodegradable and biodegradable. The conception or utilization of synthetic non-biodegradable plastics has contributed to around 10 % of the total waste disposal, either correctly or incorrectly [5]. In the 1970s, plastic waste causing environmental pollution was first reported. Plastic waste has become a global issue due to increasing amounts [6]. On the surface of the earth, the accumulation of non-degradable plastics is considered solid trash, which the animals will consume, like buffaloes and cows, and leads to the passing of animals. The increased surface area and mobility of these plastics result from the formation of particulate form by the ultraviolet radiation that leads to integration with the food chain, resulting in major disease-causing effects on living beings (Sen & Raut 2015). The accumulation of toxic chemicals due to the dumping of plastic wastes in marine life causes significant problems such as gastrointestinal blockages, improper digestion, and reproductive issues in aquatic organisms. Marine environment minimum of numerous species, including around 44 % of seabirds and 86 % of sea turtles, were affected by plastic pollution [7].

More than 600 species, varying from microorganisms to whales, were hardly impacted by aquatic plastic pollution, primarily by ingesting them (Wilcox et al., 2015). There are numerous types of polymers, such as polycarbonate, nylon, polyethylene, polystyrene polypropylene, polyurethane, polyvinyl chloride and polytetrafluoroethylene. To decompose these types of plastic polymers, there are various categories like thermo-oxidative degradation, photodegradation, biodegradation and hydrolytic degradation. Thermo-oxidative degradation, photodegradation, biodegradation and hydrolytic degradation are the different methods used to degrade those plastics, whereas, under abiotic degradation, photodegradation and thermos-oxidation take place and biotic degradation process by the action of microbes [7].

The term “breakdown of a substance catalyzed by enzymes in vitro or in vivo” was defined by the IUPAC describing the biodegradation. The biodegradation can be categorized by (i) primary, resulting in the loss of specific properties by changing the chemical structure of a substance; (ii) environmentally acceptable, unwanted properties from the compounds are removed, making them biodegradable. This mimic primary biodegradation, also depending on the circumstances under which the products are discharged into the environment; and (iii) ultimate, which involves complete compound breakdown to fully oxidized or reduced simple molecules (such as carbon dioxide/methane, nitrate/ammonium, and water). In aerobic (presence of  $O_2$ ) or anaerobic (absence of  $O_2$ ), it should be emphasized that the biodegradation of products can be more dangerous than the naturally degrading material [3]. In addition to other degradations, the eco-friendliest and pollution-free process was preferred as a biodegradation method. In this biodegradation process, they are incorporated with microbes such as bacteria and fungi. When plastics are used as a food source by environmental conditions such as temperature and pH, fungi will grow over the surface. They will release enzymes like lipase, cutinase, esterase, protease, carboxylesterases, and various pro-oxidant ions, which also help to decompose the plastics. Enzymes enhance the hydrophilicity of plastics by hydrolysis or oxidation, which causes biodegradation. In this process of biodegradation, the solvent activities affect the enzymatic activity, lead to growth in polarity, and reduce the viscosity [7]. According to Tournier et al. [8], by 2026, the global market for enzymes used in industrial applications is estimated to grow from \$6.4 billion in 2021 to \$8.7 billion.

Microorganisms regulate the process of biodegradation by incorporating the physico-chemical changes of plastics into monomers that can be degraded to  $CO_2$  and  $H_2O$ . Microorganisms, such as fungi, can biochemically break down and consume and absorb complex materials, foreign particles, and resistant substances for their energy. A number of mechanisms and organisms have been studied to promote and enhance the biodegradation of harmful polymers. To give an example, adding some particular bacteria by carrying modified plasmids from polluted areas can shift the catabolic genes to native bacteria, making it better for the biodegradation of foreign substances [9]. The main properties of plastics, such as their crystallinity and molecular weight, make the effectiveness of biodegradation by the microbes. The enzymes that degrade polymers are exo-enzymes which perform outside the cell. They can react from oxidative to hydrolytic activity, generally working for the biodegradation of polymers called depolymerization. Those exo-enzymes can make the polymers into monomers by entering into the microbial cell to complete biodegradation [10]. Factors like polymer structure, morphology, molecular weight, chemical treatment, surface characteristics, and availability properties affect the biodegradation process. Polymer structure: The linkage of polymer gets broken when in contact with microorganisms and the hydrolase enzymes. Polymers that contain both hydrophilic and hydrophobic structures are easier to degrade than a polymer, including just a single structure. Polymer morphology: The secreted enzymes can more easily attack the amorphous parts than the crystalline part. Melting temperature ( $T_m$ ) also affects enzymatic biodegradation; an improvement in the melting point can reduce the biodegradation of polymers [1]. Factors influencing enzymatic biodegradation have been discussed in detail in Table 1.

The chemical composition, weight loss, emission of  $CO_2$  and the mechanical properties of the polymer identified its biodegradation. However, in early studies, biodegradation was recognised as the result of the physical properties of polymers, such as crystallinity, water uptake, and tensile strength. It is able to understand the variation of genes in the microbes or enzymes which degrade the plastics. This reduces pollution waste by changing it into carbon sources or other alkane products using biotechnology microbes [6]. The incorporation of plastics into the environment can be through normal conditions that can create a new functional group by changing the surface property of the polymer. Under certain conditions like weathering, polymer structure can be continuously degraded. Factors like mechanical energy, ozone, radiation, and heat are provided, as well as mechanical hardness and discolouration of polymeric structures. The typical symptoms of the degradative cycle are often polymeric mass rigidity and discolouration in which radiation, mechanical energy, ozone and heat are essential factors. Propylene and ethylene copolymers were manufactured in more than 40 % of polymers made every year with no manufacturing or balancing the vision. This causes a rise in the amount of waste while presenting the disposal of waste issues [10].

Conventional plastics like PP, PE, PET, PS, and PUR are well known for the persistence of the environment. Every polymer undergoes the fragmentation slowly to form monomers for many years to degrade it due to biological and physical degradation. Commercially accessible polymers are not searching for biodegradable compounds, according to Glaser [10]. The current point of view offers guidance. The current viewpoint supports polymer biodegradation, aiming to transform these recently discovered biodegradation processes into techniques that can most effectively support ongoing efforts to manage plastic trash. Cai et al. [19] have reported that *Bacillus* sp., *Pseudomonas* sp., *Nocardia* sp and *Mycobacterium* sp. are polyethylene-degrading bacteria. Initially, plastic gets reduced to a small size by the microorganisms that colonize its surface; first, that breaks into monomers, which can be consumed as food to the microbial cells, and after that, these monomeric units act inside their cells through enzyme biodegradation, which used the monomers by source as carbon for their growth. This method can increase the reaction of microbes through physical or chemical processes, including freezing, heating, thawing, cooling and chemical degradation.

**Table 1**  
Factors influencing enzymatic biodegradation.

| Factor                     | Description                                                                                             | Impact on Biodegradation                                                | Reference |
|----------------------------|---------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|-----------|
| pH level                   | The degree to which the environment where biodegradation takes place is acidic or alkaline.             | Enzyme activity can be increased at ideal pH values.                    | [11]      |
| Temperature                | The action of environmental temperature on enzyme activity and growth leads to degradation rates.       | Higher temperatures increase the degradation rates of polymers.         | [12]      |
| Concentration of substrate | The enzyme degrades the concentration of the material.                                                  | Higher concentrations may increase the rate until saturation.           | [13]      |
| Enzyme Concentration       | The amount of enzyme available for the biodegradation process.                                          | Higher enzyme levels of the degradation process can increase the speed. | [14,15]   |
| Presence of Inhibitors     | Chemicals or substances that may inhibit enzyme activity and lead to the reduction in degradation rate. | Inhibitors can significantly reduce the rate of biodegradation.         | [16]      |
| Availability of Oxygen     | The availability of oxygen in aerobic biodegradation processes can increase the rate of reaction.       | Oxygen is crucial for aerobic biodegradation processes.                 | [17,18]   |

Mineralization of simple monomers occurs when the enzymatic biodegradation takes place and releases H<sub>2</sub>O, CO<sub>2</sub>, N<sub>2</sub>, CH<sub>4</sub> and various other chemical products. In order to destroy these types of hazardous plastics from the environment, it can be beneficial to utilize these end products further [20]. Based on this, the objective of this study is to investigate and evaluate the potential of enzymatic biodegradation as a sustainable approach for reducing the environmental issues associated with synthetic polymers.

The study specifically indicates to investigate the mechanisms of enzymatic biodegradation of several polymers, including polyethylene (PE), polyurethane (PU), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS) and polypropylene (PP). Enzymes from microorganisms like *Pseudomonas*, *Bacillus*, *Ideonella*, and *Aspergillus* that are essential for degradation are identified and studied using this method. An approach to plastic waste management that relies on the enzymatic biodegradation of synthetic polymers; this approach highlights processes, synergistic techniques, and industrial uses, such as the incorporation of bioreactors. The review stands out by exploring into enzymes found in adverse conditions and the integration of physical and biological methods to improve biodegradation efficiency. It also offers novel perspectives on sustainable waste management.

## 2. Mechanism of action of enzymes in biodegradation of polymers/plastics

The mechanical process of microbial enzymes acting on the surface of polymers is done using the biodegradation method. Microorganisms like fungi bacteria and their composition bond with the polymer sheet,

release the enzymes, and expand on it, using it as a medium for their growth and nutrition. Therefore, water (H<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), and methane (CH<sub>4</sub>) are the end products of the mineralization process of polymers that make slow biodegradation [7]. Hydrolases are the significant enzymes utilized in the biodegradation of plastic materials present in the environment. The class of enzymes, "Hydrolases" represents the third class of enzymes that involves cleavage of the chemical bond in the presence of water, which makes the breakdown of a larger molecule into smaller molecules [20]. Chain cleavage methods are preferred in amorphous regions during the hydrolytic breakdown of polymers, increasing polymer crystallinity. The process of hydrolytic degradation includes the diffusion of water molecules, which starts in the amorphous areas and can trigger the cleavage of ester bonds [21]. Polyester-based polymers undergo depolymerization by the ester bond hydrolysis linkage. Ester bond hydrolysing enzymes like esterases, lipases, proteases, ureases, or cutinases with different substrate preferences and interfacial activation facilitates this hydrolytic attack. The enzymes responsible for depolymerizing different plastics are highly substrate-specific [22]. The mechanical action of enzymatic biodegradation of polymers is depicted in Fig. 1.

The plastic solid wastes from the weight loss experiments undergo several chemical studies to explore possible enzymatic biodegradation mechanisms of polyesters. DSC, FT-IR, <sup>1</sup>H NMR, GPC and TGA were used to study some solid wastes of PCL, PBS and PBSA polyesters that have reacted with several enzymes. The spectra show all the enzymes involved with polyester films during cutinase biodegradation. The spectra of polyester films during biodegradation of cutinase include all the enzymes. It was reported that the BA/BS ratio of PBSA films didn't

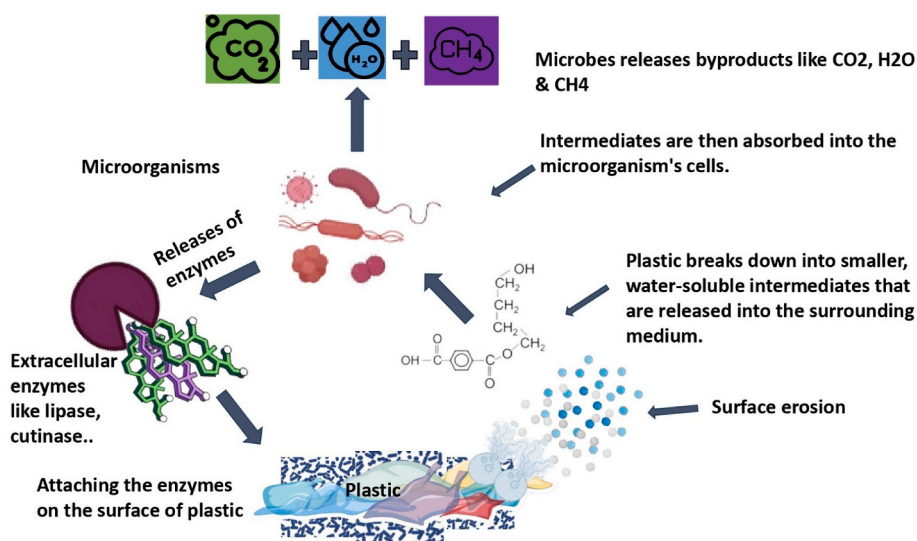


**Fig. 1.** Mechanism of action of enzymes in biodegradation of polymers.

change in terms of enzymatic biodegradation, which did not favour one over the other component. One of the processes used to study the amount of OH end groups was  $^1\text{H}$  NMR analysis. By analyzing the standard value of normalized integrals of protons in the polymer chain,  $\text{CH}_2\text{OCO}$  with normalized integrals of peak on the  $\text{CH}_2\text{OH}$  end groups was obtained. The amount (about 1/2 mol%) improved slightly and contained high molecular weight noticed in GPC [23]. The 37-kDa PHBV depolymerase enzyme from the *Bacillus* sp. AF3 has an efficient biodegradation in PHBV. Certain similar studies have been done on *Actinomadura* sp. AF-555 for the PHBV biodegradation and comparable results were identified for the biodegradation as analyzed by FTIR, which involves the cleavage of C-H bonds and O-R groups or ester ( $>\text{C}=\text{O}$ ) and SEM examination, which calculates the surface pits and roughness [24]. Cutinase from the *Humicola insolens* (HiC) and cutinase one from *Thermobifida cellulositica* degraded the PEF films at 50 and 60 °C. Within certain studies, both the enzymatic activity makes HiC in 1 M KPO, at 65 °C as the pH 8 were stated as best for the PEF films breakdown. However, after 72 h of the process, a complete breakage of the polymer into soluble molecules was identified. HiC usually produces FDCA, and the oligomers are hydrolyzed into their monomers gradually. PEF film substrates show a range of patterns based on the conditions of the reaction, which are used by carefully changing the parts of the process or components. This highly controlled enzymatic hydrolysis can produce opportunities for both surface polymer recycling and modification [25].

The PLA changes after a day, and the smooth sides change to hard and sharp ones. Further, the pieces become very thin, and small holes appear. The rectangular structure changes to an irregular one, forming small clusters. As studied in the micrograph, the biodegradation and absence of the PLA matrix may leave a more permeable surface. The SEM micrograph identifies the sample containing 15 wt% of crystallized nanoparticles before starting the biodegradation and after the biodegradation in 48 h. The broad peak from 9 to 27° for a neat PLA makes it purely amorphous, which can be identified in diffractograms, which makes the fastest biodegradation, even though the crystalline PLA degrades slowly. The X-ray diffraction trace differs from the clean PLA [26]. Hegyesi et al. [26] observed that the peaks of crystalline cellulose show a trace amount and an amorphous ring of PLA, reflecting its intensity at 16.5 and 22.7, which enlarges with enlarging its nanoparticle content. These scatterings can be noticed after their biodegradation and influence the diffractogram. The PLA is removed from the composite of cellulose nanoparticles and degrades. These results show that the polymer PLA was degraded by enzymatic compounds and the nanoparticles supported, indicating that the CNC was maintained unchanged. *Candida rugosa*, which releases the lipase, doesn't generate the biodegradation of PLA but can efficiently by the proteinase K. During the reaction, lactic acid was formed, which changes pH and strongly leads to denaturation.

Three steps of biodegradation consist of (i) microbes that attach to the surface of plastic, (ii) the carbon source of the polymer being utilized, and (iii) the biodegradation of the polymer. The microbes attach to the polymer surface and degrade it by releasing the enzymes to attain their growth (Danzo et al., 2018). Huge polymers break down into oligomers and monomers by reducing their molecular weight. A few oligomers get absorbed in the internal environment of microbes following diffusing them. The C-C structure of the polymer backbone is complicated to degrade by microbial enzymes because of the lack of hydrolyzable groups. The decrease in molecular weight is the initial step in both biotic and abiotic action. Using the ultra violet rays, the C-C groups of polymers get smoothly attacked by enzymes (Novotny et al., 2018). The enzymes like urease, laccase, manganese-dependent enzymes (which degrade lignin), protease and lipase are used for the polymer biodegradation. The PE was degraded in two days of incubation at 37 °C using the thermostable laccase enzyme (Jaiswal et al., 2019; [27]).

### 3. Enzymes released by various microorganisms responsible for biodegradation

Microorganisms are essential for the biodegradation of plastic. Different types of microorganisms break down various kinds of polymers. Microorganisms like bacteria, actinomycetes, and fungi break down plastics, both natural and synthetic. For example, nine fungal genera and seventeen bacterial genera have the potential to degrade PE. *Bacillus* bacterial isolates and *Aspergillus* sp. fungal isolates were studied as highly potential to degrade LDPE [28]. In addition, some fungal species like *Alternaria alternata*, *Fusarium oxysporum*, *Geotrichum candidum*, and *Trichoderma* sp., can break down plastics between 17 and 95 % of their molecular weight, while bacteria like *Pseudomonas* spp., *Staphylococcus* spp., *Escherichia coli*, *Corynebacterium* spp., and *Micrococcus* spp. can break them down by 45–56 % [29].

#### 3.1. Bacterial species

##### 3.1.1. *Pseudomonas*

*Pseudomonas* spp. produces unique enzymes like esterase, lipase, and serine hydrolase [30]. Various degrees of efficiency have been studied for the biodegradation of polypropylene, polystyrene, polyethylene, polyethylene glycol, polyvinyl chloride, polyurethane, polyethylene succinate, polyvinyl alcohol and polyethylene terephthalate by the *Pseudomonas* sp., which isolated from environmental matrices [31]. For example, PE can be degraded by bacteria such as *Mycobacterium* sp., *Pseudomonas* sp., *Nocardia* sp., *Bacillus* sp. [19], *Acinetobacter pittii* IRN19, *Micrococcus luteus* IRN20, and *Pseudomonas putida* IRN22 [32], along with strains like *P. aeruginosa*, *P. syringae*, and others [33]. PE film weight reduction has been achieved using *P. fluorescens* (22 %) and *P. putida* (18 %), facilitated by enzymes like alkane hydroxylase (Kumar et al., 2015; [34]). Since PP treated with heat oxidation shows greater weight loss than PP pretreated with brief UV, it was studied that *P. stutzeri* would preferentially target the ester bonds in polypropylene. Similarly, a PS heteropolymer with maleic anhydride attached with trace quantities of lactose, sucrose, or glucose was broken down by *Pseudomonas* sp. NCIM 2220. Additionally, an unidentified *Pseudomonas* sp., has the ability to degrade a high-impact PS made of a combination of PS and polybutadiene [31].

Fewer microorganisms degrade polyethersulfone (PES) compared to polycaprolactone (PCL). *Pseudomonas* sp. AKS2 effectively degrades PES (Rana, 2019; [5]). Lipases from *P. aeruginosa*, *Burkholderia cepacia*, and *Bacillus subtilis* degrade PCL and P4HB [35]. PU traits that hinder biodegradation, a number of *Pseudomonas* species have been found to be PU degraders, including *P. cepacia*, *P. aeruginosa*, *P. protegens*, *P. chlororaphis* and *P. fluorescens*. *Pseudomonas chlororaphis* degrades polyurethane (PU) using papain and urease. According to reports, *P. aeruginosa* AKS9 can use Impranil DLNTM and PU diol, a commercial kind of polyester PU. Aliphatic polymers like PES, PBA, PPA, and PEA degrade via hydrolase enzymes, including PHB depolymerase and lipase. Bacteria such as *Rhodospirillum rubrum*, *Pseudomonas lemoignei*, and *Bacillus megaterium* are associated with PHB depolymerase activity [30,31]. PET, PVC and PP are the polymers shown to biodegrade the least by *Pseudomonas* sp [31].

##### 3.1.2. *Bacillus*

Khalil et al. [36] were to identify the stands in bacteria *Brevibacillus borstelensis* AK1 with 454 sequencing technique for the PE biodegradation. The enzymes like polyphenol oxidase, laccase, hydroxylases and monooxygenase contain the AK1 strand used for the polymer biodegradation. A hydrolase-releasing bacteria, *Bacillus* sp. *BCBT21* secretes chitinase, xylanase, CMCase, protease and lipase, which are used to degrade plastics [30], were processed at 55 °C during the treatment with less activity and the activities were reduced over the reaction time. Higher temperatures cause more biodegradation for the plastic, which is induced by these hydrolase enzymes by the *Bacillus* sp. *BCBT21* plays a

key role in VHL bag biodegradation during the reaction. *Bacillus* sp. BCBT21 can also be isolated from composting agricultural residuals, which is capable of breaking down biodegradable and oxo-biodegradable plastics from various resources [37].

### 3.1.3. *Ideonella*

*Ideonella sakaiensis* 201-F6 secretes two hydrolytic types of enzymes that are widely studied for Polymer Degrading Enzymes. These enzymes, MHETase (MHET-digesting enzyme) and PETase (PET-digesting enzyme) degrade the PET and some hydrolyzable polymers [29,30,38]. The PET converts to MHET (mono -2-hydroxyethyl terephthalic acid) by PETase, which also produces the bis (2-hydroxyethyl)-TPA and terephthalic acid (TPA) that are secondary products. Later, the MHET converts into two monomers, such as ethylene glycol or EG and TPA, by the MHETase enzyme [30]. The *I. sakaiensis* bacteria secrete the PETase enzyme and degrades the ester bond in PET, which is disoriented without any treatment [39]. The biodegradation of PET bottles by *Ideonella sakaiensis* has been shown in Fig. 2. Yoshida et al. [38] identified these two hydrolytic enzyme assay protocols to characterize PETase and MHETase, which can be applied to evaluate new enzymes that target PET and its hydrolysates.

## 3.2. Fungal species

Polymers like PLA, PBS, PCL and PBSA degrade the 64 cutinase-like enzymes secreted by *Pseudozyma antarctica* strain JCM 10317. They also can degrade using 65 cutinase-like enzymes, which are isolated from the *Paraphoma*-related fungal strain B47-9, including 66 PBS and PDLLA (poly-DL-lactide), but do not degrade the PLLA or PHB. The cutinase or cutinase-like enzymes are more commonly reported fungal enzymes that degrade PBS 69 [40]. According to studies, PBS and PCL degrading enzymes are cutinases or lipases, and proteases are the most effective degrading enzymes for PLA polymers. Esterolytic enzymes like lipases, cutinases, proteases, and esterases are commonly used for the biodegradation of bioplastics [41]. *Aureobasidium pullulans* fungal species were found as the first microorganism degrading synthetic polymers reported about 50 years ago, with the biodegradation of polycaprolactone [8].

### 3.2.1. Yeast

**3.2.1.1. *Pseudozyma*.** *Pseudozyma antarctica* (PaE), a leaf surface yeast, can degrade PLA, PBSA, and PBS films by secreting specific enzymes, unlike PCLE (*Paraphoma*-related cutinase-like enzyme), which cannot

degrade PLA. PBAT films are degraded by CfCLE from *Cryptococcus flavus* GB-1 and PCLE from *Paraphoma* B47-9. CmCut1 from *Cryptococcus magnus* degrades other polymers but not PBAT. *Pseudozyma* spp., classified as basidiomycetous phyllosphere yeasts, efficiently degrade PBSA and PBS used in agricultural mulch films. The enzyme PaE, secreted by *P. antarctica* JCM10317, rapidly degrades PCL and PBSA films with carboxylic units containing C6 acyl bonds, outperforming its activity on PLA and PBA. *Paraphoma* sp. B47-9, an ascomycetous fungus extracted from barley, secretes PCLE (19.9 kDa), structurally similar to fungal cutinases from *Glomerella cingulata* (54.2 %) and *Fusarium solani* (57.3 %), but only 21.3 % similar to PaE [42,43]. The process flowchart of degradation of PLA by the *Pseudozyma antarctica* (PaE) is presented in Fig. 3.

**3.2.1.2. *Candida*.** *Candida antarctica* (CALB), a yeast species which secretes the lipase enzyme, is able to catalyze the TPA with the connection of *Humicola insolens* releases the cutinase and can degrade the PET polymers [39]. For the biodegradation of PCL films, the lipase that *C. antarctica* secretes is more effective than that of cutinase, which *F. solani* secretes. Vast amounts of weight loss and degraded deeply of PCL films by lipase enzymes [44].

**3.2.1.3. *Fusarium*.** PCL and PBS degrade using cutinase from the *Fusarium* sp. FS1301 68 [40]. The *F. solani* releases a gene encoding cutinase that is copied and excessive in *Pichia pastoris*. The PBS breakdown was studied using the recombinant cutinase from the *F. solani*. They have been studied to develop more methods for the biodegradation of plastic wastes, and the mechanical degradation of PBS films has been investigated [45]. PBS degradation is revealed better when using a PBS degrading strain, *Fusarium* sp. FS1301. They have used various studies and managed the polymer waste by identifying its mechanical degradation availability it. Mao et al. [46] isolated that it is very common to the cutinase in *F. solani* with the PBS depolymerase in *Fusarium* sp. FS1301. They also identified that it can be helpful for other possible degradations of plastic waste.

### 3.2.2. Mold

**3.2.2.1. *Aspergillus*.** The *Aspergillus* genus exhibits strong polymer-degrading abilities, targeting polymers such as PP, PE, and HDPE. *A. niger* (ITCC No. 6052), isolated from plastic dump sites, effectively degrades HDPE, while *Rhizopus oryzae* strain NS5 contributes to LDPE degradation [19]. Esterase enzymes from *Aspergillus tubingensis* and

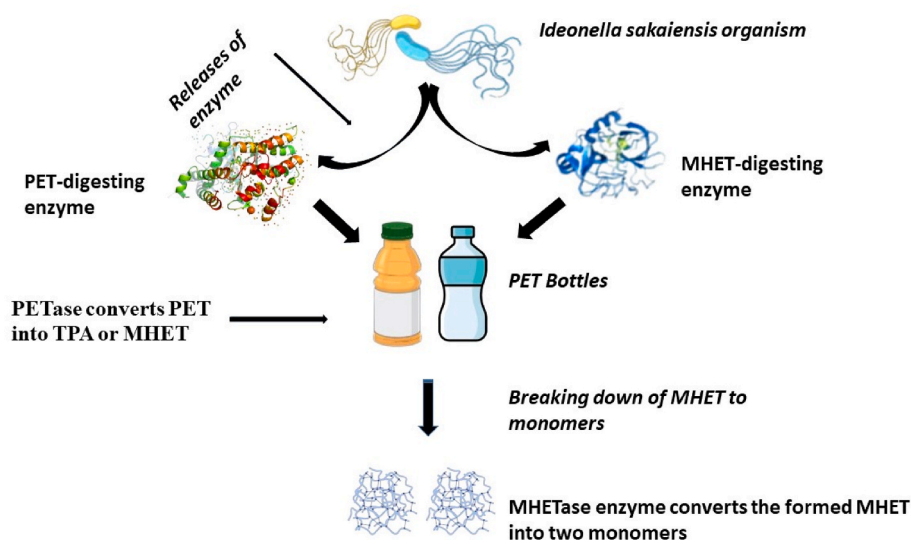


Fig. 2. The biodegradation of PET bottles by *Ideonella sakaiensis*.

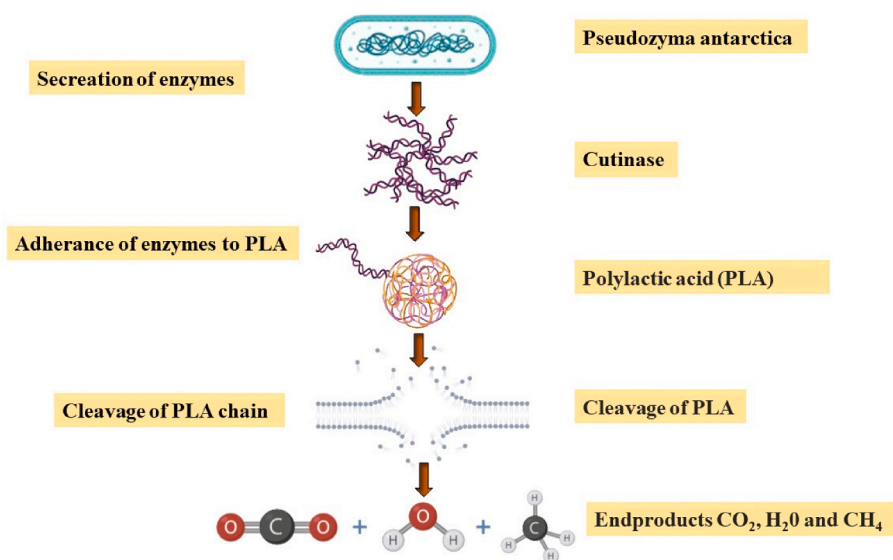


Fig. 3. The degradation of PLA by the *Pseudozyma antarctica* (PaE).

*A. flavus* play a crucial role in plastic degradation [7]. Thermo-tolerant PHA depolymerase from *A. fumigatus* M2A operates optimally at pH 8.0–9.0 and 70 °C, while cutinase from *A. oryzae* RIB40 targets PBSA and PBS. PHB depolymerase (PhaZ) from *A. fumigatus* strains Z5 and Af293 effectively degrade PHB, PHV, and related polymers. Additionally, *A. clavatus* NKCM1003 secretes PESu hydrolase, which degrades PES and PHB but no other polymers like PVL or PBS [40,41].

**3.2.2.2. *Penicillium*.** *Penicillium* species demonstrate the ability to degrade various plastics. *Penicillium oxalicum* strain DSYD05-1 was found to degrade PHB, PBS, and PCL [41]. *P. simplicissimum* produces enzymes, including manganese peroxidase and laccase, contributing to PE degradation. Spectrometric techniques confirmed their enzymatic activity, with crude extracts of these enzymes inducing morphological changes and weight loss in PE, as observed through FTIR analysis [47]. Among the two enzymes, manganese peroxidase (60 kDa) exhibited higher biodegradation efficiency (0.6 %) compared to laccase (66 kDa), which had an efficiency of 0.5 %, indicating that *P. simplicissimum* has significant degradation potential for PE. Additionally, oxidative degradation of LDPE treated with peroxide and laccase activities from *A. terreus* and *Penicillium* sp. resulted in notable weight loss [48].

**3.2.2.3. *Rhizopus*.** The enzymes such as lipases, esterases and hydrolases were used to degrade the PCL degradation, which microorganisms like *Rhizopus arrhizus* can secrete [30]. The subclass of the esterase enzyme, lipids, catalyzes the hydrolysis of the lipids and produces some fungi species. They include *Rhizopus delemer*, which degrades to about 53 % polyester PU in 24 h of activity. The hydrolysis of PBSA (polybutylene succinate-co-adipate) and PBS (polybutylene succinate) were degraded using the ipase enzyme secreted from the yeast *Cryptococcus* sp. [7].

### 3.3. Composite

The polythene bags and plastic cups were degraded during the one-month period of treatment by bacteria and fungi. The 8.16 % of plastics and 20.54 % of polythene were degraded by bacteria, which is *Pseudomonas* spp., but 7.26 % of plastics and 28.80 % of polythene can be degraded by fungi, which is *Aspergillus glaucus* [49]. Mohanan et al. [6] isolated that to degrade the PP, the fungus *Aspergillus niger* and bacteria such as *Pseudomonas* and *Vibrio* were used. Without using any pretreatment, the biodegradation of atactic PS was caused by *Curvularia*, a fungal species, and the PS is used as a pure strain of *P. aeruginosa*. The

combination of hydrolase and oxidoreductase enzyme treatment with fungal and bacterial strains was reported to have a high range of biodegradation in plastic. Inducing the biodegradation of plastic enzymes such as cutinase, esterase, hydrolase, urease, and laccase and the factors influenced by *Bacillus*, *Staphylococcus*, *Penicillium*, *Pseudomonas*, *Pestalotiopsis*, *Phanerochaete*, *Streptococcus* and *Aspergillus* were reported by Ref. [37]. PET plastic has an active degradation by novel cutinases found in fungal species like *Humicola insolens* and *Fusarium solani* [39]. Using the isolated bacteria from waxworm, beworm is a German startup which identifies the enzymes incorporated in PE biodegradation, which can be used in a reactor after abiotic pretreatment. Tournier et al. [8] found that the larvae of *Plodia interpunctella* were capable of degrading PE films, which is a gut microbial community.

### 3.4. Key enzymes in polymer biodegradation

#### 3.4.1. Hydrolases: enzymes like esterases, proteases and lipases

The use of water to catalyze the cleavage of chemically bonded structures by breaking down larger molecules into small ones by hydrolytic enzymes was known as hydrolase. Proteases, amylases, phosphatases, esterases, acylases and lipases are examples of hydrolases. The petroleum pollutants from oil spills, carbamate insecticides, and organophosphates were hydrolytically degraded using haloalkane dehalogenases, lipases and cellulases [50]. The biodegradation of PUR (polyurethane) and PET (polyethylene terephthalate) was used with esterases like lipases and cutinase. Cutinases, proteases, lipases, carboxylesterases, and fungal hydrolases tend to increase the plastic hydrophilicity and modify the surface area. In the presence of hydrolyzable chemical structures of bonds, these enzymes can react to the biodegradation of PUR and PET [9]. Based on the substrate preference, the esterases and lipases are primarily unique.

Lipases are more effective with water-insoluble, which has long-chain triacyl-glycerol, but water-soluble long-chain triacylglycerol is more active with esterase hydrolyze enzymes. It also reported that esterase and lipases are more effective catalysts for the degradation of aliphatic polyesters [23]. The bacteria *Pseudomonas* secreted lipases particularly [51,52], *Alcaligenes* genera and *Lactobacillus* and fungal-extracted lipases from *Candida* [53,54]. The more effective enzymes for the biodegradation of aliphatic polyesters were produced by *Rhizopus*, *Mucor*, and *Aspergillus*, including the hog liver esterase enzymes. Extracellular triacylglycerol acyl hydrolases that are fungal lipases (EC 3.1.1.3) able to hydrolyze the ester linkage bonds, which are

from the tri-, di- and mono-glycerides that are insoluble substrates into glycerol and free fatty acids. So, methods like digestion, absorption and reconstitution were included in the lipid metabolism by lipase enzymes. This enzyme can be secreted from habitats such as deteriorated food, waste, and contaminated soil [9]. *Acremonium*, *Beauveria*, *Eremothecium*, *Geotrichum*, *Mucor*, *Penicillium*, *Rhizopus*, *Aspergillus*, *Alternaria*, *Candida*, *Fusarium*, *Humicola*, *Ophiostoma*, *Trichoderma* and *Rhizomucor* are the lipase producing fungi which are in main genera. The various industrial applications, such as textile, food, and manufacturing areas, as well as the development of cosmetics, pharmaceuticals, and detergents, were generally used for the fungal lipase enzyme, mainly for the degradation of PU and fatty wastes used by lipase enzymes [9]. Proteases are hydrolytic enzymes that are used to separate the peptide linkage of protein utilizing the protease hydrolytic enzyme and are classified into alkaline, acid and neutral [55]. The biodegradation of aliphatic polyesters using several serine proteases like proteinase K,  $\alpha$ -chymotrypsin, subtilisin, elastase and trypsin makes an effective biodegradation of PLA. *Bacillus* sp. secretes various proteases, and proteinase K was studied for the PLA degrading method. It has been reported that the PLA degrading process of proteases has seen an enantioselectivity towards the PLLA (poly-L-lactic acid) and PDLA (poly-D-lactic acid), whereas to degrade the PDLA, lipase type of cutinase-like enzyme is required [23]. Table 2 shows the mechanism of action of Enzymes involved in polymer biodegradation.

### 3.4.2. Oxidoreductases: enzymes like peroxidases and laccases

The electron transfer between molecules, the reactant, to a different molecule is the oxidant; oxidoreductases enable the electron transfer from one molecule (the reductant) to another (the oxidant). Oxygenases, peroxidases and laccases. are the oxidoreductases. Laccases, which contain multicopper oxidases capable of performing one-electron oxidation of a broad range of substrates using O<sub>2</sub> as the electron acceptor, can transform various persistent organic contaminants like pesticides, endocrine-disrupting compounds, and pharmaceuticals [64]. Peroxidases, which contain hydrogen peroxide as the electron acceptor, are the oxidative transformation of organic pollutants through a free radical process. Lignin peroxidases, horseradish peroxidases (HRPs), chloroperoxidases, lignin peroxidases, and manganese peroxidases (MnPs) have been used for remediation applications [50]. Fungal peroxidases and laccases, generally used for the degradation of lignin fungi, show better results in the biodegradation of PVC (polyvinyl chloride) and PE (polyethylene). Oxidoreductases (peroxidases and laccases) were included in polymer biodegradation into smaller molecules like monomers, dimers and oligomers [65,66]. Plastic polymers like PP, PE, PVC and PS require oxidation before depolymerization due to their highly

stable carbon-carbon (C–C) bonds plastic polymers [9]. The reduction of hydrogen peroxide catalyzes the oxidation of organic and inorganic compounds by the group of peroxidases (EC 1.11.1) containing oxidoreductases. Three classes of peroxide were produced: class - 1, which are intracellular peroxidases found in highly living organisms, except animals; class - 2, which are extracellular fungal peroxidases; class - 3, extracellular plant peroxidases. Lignin peroxidases (LiP; EC 1.11.1.14), versatile peroxidases (EC 1.11.1.16), manganese peroxidases (MnP; EC 1.11.1.13), and dye decolorizing peroxidases (EC 1.11.1.19), are the major fungal peroxide which depends on their use for reducing state [9]. The multicopper monomeric glycoproteins, which belong to blue copper oxidases, are laccases (EC 1.10.3.2), a class of enzymes [67]. They were included in reducing molecular O<sub>2</sub> in water and used the O<sub>2</sub> as an electron gainer to oxidize the non-phenolic and phenolic compounds [9, 68].

## 4. Aerobic and anaerobic degradation

CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub>, N<sub>2</sub> and other biomass are the natural compounds which were produced during the biodegradation of bioplastic using any microbes like fungi, bacteria or algae through aerobic or anaerobic methods [41]. H<sub>2</sub>O and CO<sub>2</sub> are the compounds produced during aerobic degradation in microbial biomass, whereas H<sub>2</sub>O, CO<sub>2</sub> and CH<sub>4</sub> or H<sub>2</sub>S are the compounds produced in anaerobic degradation [30]. The use of O<sub>2</sub> as an electron gainer for degradation makes oxygen present through the action of microorganisms, which is called aerobic degradation or respiration. They produce CO<sub>2</sub> and H<sub>2</sub>O as the end products by breaking down complex materials into simpler ones. The development of CO<sub>2</sub>(Sturm test) is a good indicator of plastic degradation and is used to measure the laboratory test for biodegradation [7]. Specific processes like respirometric methods were used to identify the increasing level of CO<sub>2</sub> or the consuming level of O<sub>2</sub> by the microbes that can occur naturally in the presence of section parameters like temperature, medium (compost, soil, etc.), humidity and pH to measure the biodegradation rate [3].

According to the origin of the microorganisms, the temperature, the type of measurement and the state of the system (liquid, solid, seawater interface, etc.) can differ the method of measuring aerobic degradation [69,70]. Biodegradation occurs in the absence of oxygen [7]. Breaking complex materials into smaller particles with the help of microbes produces CO<sub>2</sub>, H<sub>2</sub>O, CH<sub>2</sub> and biomass as their end products. With the help of sources such as electron acceptors like iron, nitrate, sulfate, carbon dioxide, and manganese utilized in the absence of O<sub>2</sub> (Alshehrei 2017). Both the aerobic and anaerobic conditions were observed for the biodegradation of PUR using two *Pestalotiopsis microspora* and isolated as

**Table 2**  
Enzymes that are included in the biodegradation of polymer.

| Enzyme   | Polymer Target        | Source Organism                                                                              | Mechanism of Action | Optimal Conditions                                   | Reference |
|----------|-----------------------|----------------------------------------------------------------------------------------------|---------------------|------------------------------------------------------|-----------|
| Lipase   | PET to TPA            | <i>Candida Antarctica</i>                                                                    | Hydrolases          | Temperature at 40 °C                                 | [56]      |
|          | PET fabric            | <i>Aspergillus oryzae</i>                                                                    | Hydrolases          | Temperature at 55 °C                                 | [56]      |
|          | Polyurethanes         | <i>CCUG 33812</i><br><i>Rhizopus delemer</i>                                                 | Hydrolysis          | Temperature (30–70 °C) and organic solvent resistant | [7,57]    |
| Protease | VHL plastic bag       | <i>Bacillus</i> sp. BCBT21                                                                   | Hydrolysis          | Temperature at 55 °C                                 | [37]      |
|          | PLA                   | <i>Tritirachium album</i> , <i>Amycolatopsis orientalis</i> & <i>Anthrobotrys oligospora</i> | Hydrolysis          | Temperature at 30 °C                                 | [7,41]    |
| PETase   | PET plastics          | <i>Ideonella sakaiensis</i>                                                                  | Hydrolysis          | 30 °C for 40 days                                    | [38,58]   |
| MHETase  | MHET to TPA and EG    | <i>Ideonella sakaiensis</i>                                                                  | Hydrolysis          | 30 °C, pH (5.5–9.0)                                  | [38,59]   |
| Esterase | PET into TA and MHET  | <i>T. halotolerans</i>                                                                       | Hydrolysis          | 30 °C–37 °C                                          | [60]      |
|          | PLGA                  | <i>M. miehei</i>                                                                             |                     |                                                      | [61]      |
| Cutinase | PLA, PCL              | <i>Alcanivorax</i> sp. 24                                                                    |                     |                                                      |           |
|          | PBS and PCL           | <i>Pseudozyma Antarctica</i> , <i>Fusarium solani</i> , <i>Aspergillus oryzae</i>            | Hydrolases          | pH 8 at 40 °C                                        | [62]      |
|          | PET film,             | <i>Humicola insolens</i> cutinase (HiC) and <i>Fusarium solani pisi</i> cutinase (FsC)       |                     | Temperature 50 °C                                    | [7]       |
|          | Polylactic acid (PLA) | <i>Aspergillus nidulans</i> and <i>Cryptococcus</i> sp.                                      |                     | Temperature 30 °C–40 °C                              | [63]      |

an effective activity of biodegradation on anaerobic growth using PUR [7]. In the presence of anaerobic bacteria, only the anaerobic degradation occurs, which means instead of CO<sub>2</sub> or O<sub>2</sub>, CH<sub>4</sub> can be produced in some instances. About 20 times more impact on greenhouse gas than CO<sub>2</sub> by composting polymers in anaerobically [71], whereas this CH<sub>4</sub> can be captured and burned for the production of H<sub>2</sub>O and CO<sub>2</sub> and thermal process in the industrial process. Methane emissions from anaerobic polymer degradation represent a significant global environmental challenge, with CH<sub>4</sub> having a 28–36 times more potential for global warming higher than CO<sub>2</sub> over a century. These emissions contribute substantially to greenhouse gas dynamics, particularly in waste management scenarios where uncontrolled decomposition can accelerate climate change mechanisms [72,73]. Polymers include PLA, polyhydroxyalkanoates, polycaprolactones and thermoplastic starch at elevated temperatures that are feasible for biodegradation in anaerobic conditions [74]. Temporal logging of water can occur due to the biodegradation of biopolymers in anaerobic soil conditions like soils and peat areas with a stagnant property [75]. A newly founded bacteria that can be used for the biodegradation of anaerobic lignin leads to a proper result for the lignin biodegradation [76].

Anaerobic degradation of cellular paper (CA) was found, and certain common rates were identified in the aerobic and anaerobic conditions. The anoxic soil conditions developed after the flooding of the field research location created a decrease in TPS biodegradation. These results can expand the anaerobic terrestrial studies of future research [75]. Biogas production occurs through complex waste materials degradation by an anaerobic mechanism, which is used to make vehicle fuels, electricity and chemicals [77]. The organic fraction of multiple solid wastes (OFMSW) was used as the common anaerobic digesters are one source of waste, which includes paper, cardboard (cellulose), food waste (pectin), plastics and wood (lignocellulose) [78,79]. Certain materials like plastics, cellulose and lignocellulose were highly required for the synergy between the secreted enzymes and those microorganisms, which can effectively degrade into substrates for biofermentation [79]. By selecting the inocula from the environment, the maximum number of waste degradation can occur for the naturally breaking down as the substrate. One of the naturally degrading in the rumen is lignocellulose digested in anaerobic conditions, and certain groups were cultivated [80,81]. Microorganisms release enzymes and get divided during anaerobic degradation that resist the polymers and produce fermented products like methane. However, the microbes remain not fully utilized for the degradation of waste because it's getting difficult to identify and get the interaction between them during the degradation, mainly through anaerobic digestion. Certain anaerobic fungi show changes in byproducts of lignocellulose digestion by increasing its carbohydrate-digesting enzymes [79].

## 5. Biodegradation of various plastics

For the biodegradation of polymers, microbes secrete certain kinds of enzymes like peroxidase, lignin, amylase, esterase, laccase, and manganese peroxidase as potential catalysts. The three lignolytic enzymes are laccase, manganese peroxidase and lignin peroxidase. They include laccase or phenol oxidase, heme peroxidase, which consists of manganese peroxidase, versatile peroxidase and lignin peroxidase. Hydrolysis and oxidation are the two reactions that involve plastic degradation. Catalyzing the hydrolysis reactions of carbonates, esters, and glycosidic bonds of various polymers and amides for the production of monomers is known as a hydrolase reaction. While catalyzing the reducing and oxidizing reactions of ethylene, amide, urethane, carbonate and others was known as the oxidoreductase reaction [30]. The carbonyl groups of polyethylene were converted into alcohol at the first step of degradation catalyzed by the enzyme monooxygenase. Then, the alcohol is converted into aldehyde using the alcohol dehydrogenase catalysts, and later, the aldehydes are converted to fatty acids using aldehyde dehydrogenase enzymes. They will go for the more process into the microbe cell by the

β-oxidation way. Meanwhile, the PE polymer breaks down into carboxylic acids, which are carried by laccase enzymes, forming the acids that will further go with coenzyme-A through fl-oxidation. This breaks down the carboxylic acids to produce acetyl-CoA results for the further metabolism included in citric acid cycles. The final product as water and carbon dioxide for the PE degradation due to the catalyzed laccase enzyme formed from microorganisms [30]. *Bacillus* and *Pseudomonas* were isolated from the highly polluted areas for the biodegradation of PET, metabolic compounds, and other substrate materials [39]. Table 3 shows common polymers, their applications and their potential impact on the environment.

### 5.1. Polyethylene (PE)

Polyethylene is the largest tonnage of polymer material, which has the simple structure of any plastic. Toughness, good electrical insulation over a broad range of frequencies, low price, flexibility, thin films of certain grades, and transparency. Good processability and chemical resistance are the main appealing features of PE [96]. Cutinases, reductases, laccases, esterases, hydroxylases, and lipase peroxidases are the enzymes released from bacterial and fungal sources that degrade the PE. The main enzyme which degrades the PE by two lignin is manganese peroxidase, and the other one is alkane hydroxylase, which is isolated from *Pseudomonas* sp. [97]. For the breakdown of low molecular weight, *P. aeruginosa* released alkane hydroxylase together with rubredoxin and rubredoxin reductase enzyme for PE. The other organisms such as Laccases from actinomycetes, *Rhodococcus ruber* [97] and fungi like *Pleurotus ostreatus* (Gomez-Mendez et al., 2018) and *Aspergillus flavus* (Zhang et al., 2020) can degrade the PE, which they act as the backbone as PE hydrocarbon via oxidation method [97].

The polymer structural changes under SEM were studied by calculating weight loss and some chemical modifications of functional groups using FTIR, which were used to observe the biodegradation study of PE. Surface topography and weight loss were the most significant changes that have been defined as a result of various degradations of PE. *Pseudomonas* sp. can degrade and metabolize the plastic polymers and its end products. It has a hydrolytic enzyme or extracellular oxidative activity that higher the biodegradation level and maintains the interaction of the polymer surface and the biofilms. Using SEM and AFM (atomic force microscopy), the structure, corrosion, cracks, and surface roughness made by the microbes can identify the biodegradation of HDPE film [98]. Using the response of polymer surface, which is secreted by *P. oxalicum* NS4 (KU559906) and *P. chrysogenum* NS10 (KU559907), have reported degrading the LDPE and HDPE films by optimizing the media and improving the mycelium weight. The PE-degrading fungi strains form biofilm, and the morphological changes on the surface of HDPE and LDPE are caused by sure pits, cracks, and undulations. It has been reported that PE degradation by *Enterobacter* sp. D1 from the guts of wax moth *G. mellonella*. Over 14 days of incubation, they studied using SEM and AFM to identify the strain of D1 that is able to form the colonies across the PE film and degrade the PE film surface. After the PE film treatment, HPLC-mass spectrometry was used to study the D1 strain and identify the carbonyl and ether functional groups on FTIR spectra with the oxidative cleavage that produces ester, acid groups and alcohol. For the identification of the topography of the film during the degradation, AFM and SEM were used, and some formation of holes, pits, and erosions were observed. PE's mechanical and chemical properties were changed due to crystallinity and the average molecular weight [98].

### 5.2. Polyurethanes (PU)

The Polyurethanes family has a highly diverse variety of applications incorporated with different items like elastomers, elastic fibres, paints, insulators, integral skins, foams, liquid coatings, etc., which is highly promising for both consumer and production for its biodegradation [99, 84]. Enzymes like esterases, hydrolases, peroxidases, proteases,

**Table 3**  
Types of polymers and their properties.

| Polymer Type                     | Chemical Formula                                               | Common Applications                                                                                                                                                                                                                                                               | Environmental Impact                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Reference |
|----------------------------------|----------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| Polyethylene (PE)                | C <sub>2</sub> H <sub>4</sub>                                  | Flexible Packaging & Rigid Packaging Applications, Pipe and Tubing Applications, Wire and Cable Applications, Medical Applications, Automotive Applications, cosmetics, surgical tools, implants and other devices                                                                | <ul style="list-style-type: none"> <li>● Aquatic animals are frequently drawn to floating polyethylene, which can entangle them or cause them to ingest it, which may cause organ damage, genotoxicity, apoptosis and even death.</li> <li>● The presence of PE materials in the soil can increase the mobility of water-repellent organic pollutants.</li> <li>● In earthworms, polyethylene can lead to an increase in metal accumulation, which can cause abnormal gene expression and enzyme function.</li> </ul>                                                                                                                                                                                                                                                                                            | [82,83]   |
| Polyurethanes (PU)               | C <sub>27</sub> H <sub>36</sub> N <sub>2</sub> O <sub>10</sub> | Building and construction, automobile, marine, adhesives, textiles and in other industries, sealants and elastomers (CASE) industry, medicine applications, appliances, flooring and packaging applications, apparel, and coatings, foams, adhesives, sealants and elastomers     | <ul style="list-style-type: none"> <li>● Energy consumption,</li> <li>● Greenhouse gas emission</li> <li>● Biogenic CO<sub>2</sub> uptake during the biomass growth</li> <li>● Global warming potential</li> <li>● Ecosystems, human health, and resource scarcity.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | [84–87]   |
| Polyethylene terephthalate (PET) | C <sub>10</sub> H <sub>8</sub> O <sub>4</sub>                  | Water bottles, materials for packaging, textiles, plastic panels, trash cans, and various kitchen appliances, as well as automotive, building, and electronic parts, medical equipment, and diagnostic equipment                                                                  | <ul style="list-style-type: none"> <li>● Improper disposal leading to global crisis in waste management</li> <li>● Global warming</li> <li>● Depletions of stratospheric ozone</li> <li>● Ionizing radiations</li> <li>● Human health and ozone formation</li> <li>● Formation of fine particulate matter</li> <li>● Creation of ozone, ecosystems on land</li> <li>● Acidification of the land</li> <li>● Eutrophication of freshwater</li> <li>● Eutrophication of the sea</li> <li>● Earthly ecotoxicity</li> <li>● Ecotoxicity in freshwater</li> <li>● Ecotoxicity in marine environments</li> <li>● Toxicology for human cancer</li> <li>● Non-carcinogenic toxicity in humans</li> <li>● Scarcity of mineral resources</li> <li>● Scarcity of fossil resources</li> <li>● Consumption of water</li> </ul> | [56,88]   |
| Polystyrene (PS)                 | C <sub>8</sub> H <sub>8</sub>                                  | In the manufacturing of toys, refrigerators, and furniture industries, for the automotive and transportation, medical appliance, building recreational vehicles, boats and others, insulating material in packaging and as a cushioning agent                                     | <ul style="list-style-type: none"> <li>● Reduced rates of growth and reproduction, as well as oxidative stress in benthic and/or pelagic freshwater organisms</li> <li>● Aquatic creatures are presumably genotoxic because of the development of reactive oxygen species (ROS).</li> <li>● Stress from oxidation and disruption of DNA repair</li> <li>● Non-renewable energy</li> <li>● Global warming</li> <li>● Respiratory inorganic pollutants</li> <li>● There</li> <li>● In line with the increasing interest in microbial communities in toxicology, the results of PS NPL and MPL effects on bacterial populations in the soil</li> </ul>                                                                                                                                                              | [89,90]   |
| Polypropylene (PP)               | C <sub>3</sub> H <sub>6</sub>                                  | Applications for packaging, soil projects, expanding soils, tunnels, landfill liners, and geologic barriers, air filtration, water filtration, clothing, biomedical, aerospace, construction, automotive and recycled materials                                                   | <ul style="list-style-type: none"> <li>● Emission of carbons</li> <li>● Toxicity by humans</li> <li>● Underground water quality and soil and marine life</li> <li>● Ozone depletion</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | [91,92]   |
| Polyvinylchloride (PVC)          | C <sub>2</sub> H <sub>3</sub> Cl                               | Applications in the fields of mechatronics, biomedicine, robotics, building, construction, transportation, packaging, electrical, and healthcare, sensors, optical devices, PVC gel actuators and devices, including their fabrication, and the creation of novel soft actuators. | <ul style="list-style-type: none"> <li>● Marine and terrestrial ecosystem</li> <li>● Release dioxin and other air pollutants</li> <li>● Climatic changes such as global warming</li> <li>● Acidification</li> <li>● Cancer risk to humans</li> <li>● Noncancer risks to human health</li> <li>● Eutrophication</li> <li>● Ecological toxicity</li> <li>● Smog</li> <li>● Habitat alteration</li> <li>● Ozone depletion</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                | [93–95].  |

cutinases, lipases, ureases, dioxygenases, dehydrogenases, transferases, decarboxylases, ligases, isomerases and laccases from various bacterial and fungal species which degrade the PU [100,101]. PU generally has a high molecular weight and is resistant to biodegradation, whereas the urethane oligomer, which has a low molecular weight, is not always resistant to degradation. Esterase enzyme catalyzed by hydrolysis for the degradation of urethane oligomers. Through the ester linkage by esterase and lipases, PU can decrease molecular weight through microbial degradation [102]. It has been reported that the majority of PU-active enzymes were identified to be active on ester-linked PUR and,

as well as less likely on polyurethane ethers [103]. Compared with ether-linked PUR, the ester-linked PUR makes them more vulnerable to hydrolysis, which is carried by enzymatic activities because of the presence of the carbonyl group [97].

### 5.3. Polyethylene terephthalate (PET)

Polyethylene terephthalate is the most common man-made synthetic plastic in the world, and it is used in resins for packaging (like bottles and containers), textiles (like fibres), and automotive and electronics

industries [104]. TPA (terephthalic acid) and EG (ethylene glycol) are made by PET [105]. PET can be degraded by chemical processes that break down in harsh conditions like sulfuric acid at 150 °C or alkaline environments with a dangerous chemical catalyst like methyltriethylammonium bromide [105]. PET is recycled mechanically, which degrades the material properties and values, and certain microbes secrete enzymes and catabolic pathways that are able to digest the polymers [106–108]. *Thermobifida fusca* hydrolases were used for the enzymatic hydrolysis of PET polymers. The two enzymes that have been studied extensively for the biodegradation of PET are lipases and cutinases. Despite challenges in developing scalable methods for PET biodegradation, the potential benefits create new opportunities for sustainable materials management [104]. Further, numerous more enzymes like esterases [109] and carboxyl esterases have been reported for the PET-degrading ability ([103,109]; Ru et al., 2020). It has been reported that the surface erosion mechanisms were generally due to the enzymatic hydrolysis of PET [10]. PETase is the most common plastic degrading, an aromatic polyesterase isolated from *I. sakaiensis* 201-F6. PET gets metabolized by bis(2-hydroxyethyl)-TPA (BHET), MHET, and TPA enzymes. In contrast, MHETase can act as an accessory enzyme that acts on intermediates and results in ethylene glycol terephthalic acid, which can further be used to produce new PET [110]. The hydrolyzed ester bond enzymes were included, like lipases, cutinases and esterases [56]. Lipases from *Burkholderia* spp, *Thermomyces lanuginosus* and *Candida Antarctica*,; fungal cutinases from *Humicola insolens*, *Aspergillus oryzae*, *Penicillium citrinum* and *Fusarium solani* and those from actinomycetes, *T. fusca*, *Thermobifida alba*, *Thermobifida cellulolytica*, *Saccharomonospora viridis*; carboxylesterases and Esterases (*Thermobifida halotolerans*) have tested for the surface hydrophilization of PET polymers [6].

#### 5.4. Polystyrene (PS)

Polystyrene is a widely used plastic produced worldwide, mainly in packaging food and other disposable dishware. Similarly to other plastics, PS is good in its mechanical quality and its affordable price [111]. It is usually found in food containers, cassette boxes, plates, cutlery, disposable cups, construction materials (insulation), packaging foam, and compact disks. PS is divided into four categories based on usage: high-impact PS, orientated PS, PS foam, and exhausted PS [112]. It has a hydrophobic nature that is highly resistant to degradation due to high molecular weight polymer [113]. Several fungi and bacteria were reported to degrade the polystyrene. The main enzymes involved in the primary stage were the depolymerization of plastics involving an extracellular esterase from *Lentinus tigrinus*, shown in the PS breakdown. *Pseudomonas* and *Bacillus* species have also been reported for the biodegradation of PS polymers. Phenylacetaldehyde dehydrogenase, styrene oxide isomerase, styrene monooxygenase, and phenylacetyl coenzyme A ligase were some enzymes which involved in the monomer of PS before entering the TCA cycle [113]. These get involved in numerous reactions like oxidation of styrene to phenylacetate, Krebs cycle incorporation of phenylacetate, and degradation of the polymer to styrene [97].

#### 5.5. Polypropylene (PP)

After polyethylene, polypropylene is also referred to as the second most popular petroleum-based plastic material [114]. PP is a synthetic hydrocarbon polymer which is linear and thermoplastic, where a methyl-group takes place as a single hydrogen atom for every carbon of PE texture [9]. Due to its solid structure, it's resistant to degradation. The material is used in most industries for packaging, films, and disposable products ([115]; Wei & Zimmermann 2017). It is also utilized for mats, ropes, rugs, carpets, chairs and ropes, and also for the production of laboratory-required utensils like centrifuge tubes, tips for pipettes, wash bottles, Eppendorf tubes, etc. [7]. PP is almost similar to

PE, but PP has high resistance to stress cracking. It has been reported that very few microorganisms can degrade this PP, like *Brevibacillus* sp., *Rhodococcus* sp., *Phanerochaete chrysosporium* and *Bacillus* sp. [116–118].

#### 5.6. Polyvinylchloride (PVC)

Polyvinyl chloride ranks 3rd in the world in terms of the usage of synthetic plastics after PP and PE. Just before adding the plasticizers, it appeals as whitish and brittle in colour. It can be made of two forms: flexible and rigid. Rigid form PVC is then added with plasticizers like phthalates and becomes smoother and more flexible in texture. Compared with other polymers, it has high tensile strength, which is very hard and cheap [20]. Petroleum-based PVC material is widely used as a synthetic thermoplastic. Long chains of ethylene substrates comprise 56.77 % (w/w) chlorine to make up the pure PVC. They are brittle, whitish, highly hydrophobic, solid polymers resilient to chemical abrasion and soluble in tetrahydrofuran (THF) in nature [9,119]. When the PVC gets burned, it releases HCl (hydrogen chloride), which is harmful to human health and can easily be exposed as fumes to surroundings [20]. Fungal peroxidases and laccases, which are usually reacted by fungi to degrade lignin, make an effective result in the biodegradation of PVC [9]. Zhang et al. [120] have reported that numerous fungal taxa like *Deuteromycota*, *Basidiomycotina* and *Ascomycota* or the bacterial taxa like *Mycobacterium*, *Acinetobacter*, *Pseudomonas* and *Bacillus* were able to degrade the PVC by its morphological and physicochemical changes. A PVC-degrading activity of the fungus *Phanerochaete chrysosporium* has been reported for an extracellular lignin peroxidase.

#### 5.7. Composite polymers incorporated with additives

The presence of additives impacted the biodegradation of polymers. In polymer synthesis, organometallic initiators and catalysts were employed; they may function as microbicides and slow down degradation. The biodegradation process may also be impacted by the presence of plasticizers [121]. Additives like  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and hydrophobins (proteins rich in cysteine) have been shown to improve enzymatic PET hydrolysis by making PET polymers easier to access. PET hydrolysis is directly impacted by a number of variables, including temperature, pH, buffer strength, crystallinity of PET, and the type of additives used in plastics (such as plasticizers). By preventing access to the PET's ester bond, these parameters change the activity of the enzyme [122].

The biodegradation of the polymer matrix is significantly influenced by the contact of a fiber or nanoparticle with a polymer matrix, as well as the cohesiveness of the fiber and polymer molecules. The introduced nanoparticles (ZnO and TiO<sub>2</sub>) impact the PLA breakdown. According to the experiments, adding urea to the enzyme buffer and pretreating with an alkaline solution increases the rate of hydrolysis. The pace of PLA weight loss was slowed by the presence of fiber molecules [123]. It has been demonstrated that proteinase K has the biggest impact on PLA breakdown rates, both with and without flax fibers. When compared to samples that were not treated, this enzyme produced the highest degree of crystallinity and the most structural alterations in all of the samples.

Compared to pure PLA, the flax fiber-containing samples exhibited a greater affinity for enzymatic breakdown and a higher rate of biodegradation over a comparatively short period [124]. A larger starch (an organic ingredient) content in the PE-based composite material most likely leads to more noticeable deterioration and favoured microbial consumption. This has already been demonstrated for *B. cereus* and *Bacillus pumilus* in LDPE composites after a 60-day degradation period in a landfill [125]. It has been noted by Mazitova et al. [126] that the addition of starch to the composition contains additives that serve as a catalyst for biodegradation in the serial manufacturing of biodegradable polyethylene-based PMs.

The biodegradation of polyurethane (PU) samples varies depending on their composition and blending. It was discovered that the

polyurethane samples that had the lowest levels of polycaprolactone triol and the highest levels of R,S-PHB were the most deteriorated. Actually, PLA and a mixture of PU and polysaccharides (chitosan and starch) were incubated in an oxidative solution and phosphate buffer. Furthermore, the biggest influence on PU's vulnerability to biodegradation came from blending with starch. Biodegradation was accelerated in hydrolytic and oxidizing conditions when PU blended with chitosan, starch, and PLA. The samples degraded considerably more quickly in the oxidizing solution than in the neutral phosphate buffer solution. Most of the blend samples decomposed after two weeks of incubation in oxidative solution [127].

## 6. Common mathematical models for plastic biodegradation

The enzyme biodegradation model is identified using the Michaelis-Menten equation. It can be applied for data reprocessing, which has been applied as per the Lineweaver-Burk plot shown in Eqn. (1).

$$\frac{1}{V} = \frac{1}{V_{\max}} + \frac{K_m}{V_{\max}[S]} \quad (1)$$

where the maximum value as  $V_{\max}$ , the substrate concentration as  $[S]$ , the biodegradation rate as  $V$  and the Michaelis constant as  $K_m$ . For substrate A, a non-linear plot that indicates this model led to the improper fitting of data. This leads to a general estimation of the biodegradation time in relation to the first-order model. It was insufficient for applying the integrated equations of orders zero and two in comparison with the substrate [128].

The Wilkinson model [128] applied that to this substrate, yielding an apparent value of reaction order  $n = 4.2$ , with values of  $k$  in the order of  $10^{-8} \text{ day}^{-1} \text{ mg}^{-3}$ . This data can calculate the time required to reach 20 % conversion, which produces an estimated 25 days, widely equivalent to the experimental value. The differences between experimental and calculated data become unacceptable when a person wishes to express a trend over time. The estimated parameters were  $k$  in the order of  $10^{-10} \text{ day}^{-1} \text{ mg}^{-3}$  and  $n = 5.1$ , resulting in generally wrong prediction even after removing the last three points. The estimated time for 20 % of substrate degradation required 20.1 days vs 21 in the experiment, and 30 % of substrate degradation needs 44.7 days vs 80 in the experimental. So, the quality of the approach of data regression was good, as shown by the higher  $R^2$  value when compared with the 1st order model; this method was discontinued for a material C since it increases the process of maintaining various parts of a curve, which may depend on different mechanisms. The zero-order and second-order models and the Michaelis-Menten zero-order and second-order models did not work with these data.

Usually, the kinetics of the biodegradation process are modelled using four mathematical models: the Exponential Growth Model (Eqn. (2)), the Modified Gompertz Model (Eqn. (3)), the Logistic Growth Model (Eqn. (4)), and Gordon-Govind-Green-Imam-Shogren Model (Eqn. (5)).

$$w(t) = W_{\infty}[1 - \exp(-t/T)] \quad (2)$$

where the weight loss at time  $t$  is represented by  $w(t)$ , (%); the percentage chance of losing weight is  $W_{\infty}$ ; the time is  $t$  (context-dependent time unit); the time constant is  $T$  (the context determines the time unit).

$$w(t) = W_{\infty} \cdot \exp[-\exp(e \cdot R_m / W_{\infty} \cdot (\lambda - t) + 1)] \quad (3)$$

where weight loss (%) at a given time is represented by  $w(t)$ ;  $W_{\infty}$  is the percentage chance of losing weight;  $R_m$  denotes the highest weight loss rate (%) per unit of time. The variables  $t$  and  $\lambda$  represent the process's time constant and time, respectively, depending on the context.

$$w(t) = W_{\infty} / [1 + \exp(-k \cdot t)] \quad (4)$$

where weight loss (%) at a given time is represented by  $w(t)$ ;  $W_{\infty}$  is the

percentage chance of losing weight; The time is  $t$ , with a context-dependent time unit; The process's time rate constant,  $k$ , is determined by the context-specific time unit.

$$W(t) = W_{\infty^1} \left[ \frac{1}{a_{11} + a_{21}e^{-a_{31}t} + a_{41}e^{-a_{51}t^2} + a_{61}e^{-a_{71}t^3}} - \frac{1}{a_{11} + a_{21} + a_{41} + a_{61}} \right] + W_{\infty^2} \left[ \frac{1}{a_{12} + a_{22}e^{-a_{32}t} + a_{42}e^{-a_{52}t^2} + a_{62}e^{-a_{72}t^3}} - \frac{1}{a_{12} + a_{22} + a_{42} + a_{62}} \right] \quad (5)$$

Where the weight loss at a given time is represented as  $w(t)$ , (%);  $W_{\infty^1}, W_{\infty^2}$  are the weight loss potentials, (%);  $a_{1i}, a_{2i}, a_{4i}$ , and  $a_{6i}$  are the non-dimensional coefficients, (where  $i = 1, 2$ );  $a_{3i}, a_{5i}$ , and  $a_{7i}$  are the rate coefficients with the dimensions  $(\text{time}^{-1})$ ,  $(\text{time}^{-2})$ , respectively,  $(\text{time}^{-3})$ ;  $t$  is the time, (time unit depends on context) [129].

The biomass growth profile in a batch system with both exponential and stationary phases is commonly described using the logistic Equation. The logistic Equation's differential form is shown in Equation (6).

$$\frac{dX}{dt} = \mu_m X \left( 1 - \frac{X}{X_m} \right) \quad (6)$$

where  $X_m$  is the maximum cell concentration achievable in that environment (OD600) and  $\mu_m$  is the maximum specific growth rate ( $\text{hr}^{-1}$ ) in a given environment. The following formula (Eqn. (7)) for the cell concentration is obtained by integrating the logistic Equation.

$$X = \frac{X_0 e^{\mu_m t}}{1 - \left( \frac{X_0}{X_m} \right) (1 - e^{\mu_m t})} \quad (7)$$

where  $X_0$  is the initial cell concentration (OD600). A number of kinetics models have been created to explain the connection between the substrate concentration  $S$  and the specific growth rate  $\mu$ . The most popular expression for inhibition when substrate concentrations are high, and growth is influenced by inhibitor concentration is the Haldane equation, as shown in Eqn. (8).

$$\mu = \frac{\mu_{\max} S}{K_s + S + \frac{S^2}{K_I}} \quad (8)$$

where  $K_S$  is the half-saturation coefficient (ppm),  $K_I$  is Haldane's growth kinetics inhibition coefficient (ppm), and  $\mu_{\max}$  is the maximum specific growth rate ( $\text{hr}^{-1}$ ). Using a nonlinear regression approach, the experimental biomass growth profiles at various beginning concentrations of phenol were fitted to the logistic Equation. To find the model fitting parameters, the Solver add-in for Microsoft Excel 2007 was used to minimize the sum of squared errors (SSR) [130].

Fick's law of diffusion and the kinetics of enzyme-mediated polymer degradation explain the reaction-diffusion coupled process as shown in Eqn. (9).

$$\frac{\partial c}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 D \frac{\partial c}{\partial r} \right), \frac{\partial c}{\partial t} = -K \rho c \quad (9)$$

where the geometry of the problem needs the equations to be explained in radial coordinates. Here,  $D$  is represented as the diffusivity of the enzyme, and  $K$  is the constant degradation rate. The degradation has a major impact on diffusivity, which is right before the degradation; the polymer mesh prevents enzymatic activity, resulting in the diffusivity  $D_s$  defined by Lustig and Peppas as shown in Eqn. (10).

$$D_s = D_f \left( 1 - \frac{r_e}{\xi} \right) \quad (10)$$

Where the Einstein-Stokes equation is given as  $D_f$  is the enzyme diffusivity in a fluid,  $r_e$  is the enzyme molecule's hydrodynamic radius, and  $\xi$  is the polymer's mesh size. When the mesh size is smaller than the

enzyme re, this model predicts a low diffusivity  $D_s$ , and vice versa. But as soon as reverse gelation occurs, the diffusivity turns into  $D_f$ , and the mesh size abruptly diverges. This research leads us to infer that the enzyme diffusivity is significantly larger in the degraded region ( $p < p_c$ ) than in the solid polymer  $D_f \gg D_s$ ).

An analytical model that describes the radial outward propagation of a moving interface with width and speed has been created for enzymatic polymer biodegradation. It has been noted that the enzyme transport and degradation times, two competing time scales, influence the interface features. The polymer network connectivity, the enzymatic reaction rate constant, the polymer mesh size, and the concentration of the enzyme source control these time scales [131].

## 7. Challenges and future perspective

Enzymatic degradation of plastics presents challenges and opportunities for sustainable plastic waste management. Challenges include the slow degradation rates caused by the high stability of carbon-carbon bonds and the hydrophobic nature of many polymers, which make them resistant to enzymatic attack [9]. Factors like polymer crystallinity, molecular weight, and environmental conditions—such as temperature and pH, also influence the efficiency of enzymatic degradation [7]. Moreover, the high cost of enzyme production and scalability issues limit the industrial application of these processes [6].

On the other hand, enzymatic degradation offers opportunities by producing harmless by-products like CO<sub>2</sub>, H<sub>2</sub>O, and biomass, aligning with environmental sustainability goals [30]. Advances in exploring microbial enzymes, such as hydrolases and oxidoreductases, highlight their potential in breaking down various plastics under aerobic and anaerobic conditions. Synergistic approaches involving the combination of enzymatic and microbial systems have shown promise in enhancing biodegradation [9]. These developments underline the potential of enzymatic degradation as a practical solution to mitigate the environmental impact of plastic waste.

Combining bacterial and fungal degradation mechanisms could enhance the breakdown of plastic polymers. Synergistic approaches may increase the potency of biodegradation strategies, taking advantage of the specific strengths of each microorganism. For example, bacteria might begin breaking down a polymer, forming intermediates that fungi can further consume. The exploration of enzymes from various environments, such as plants, marine, and animal, not only diversifies the enzyme sources for sustainable plastic degradation but also introduces the unique enzymatic properties that can be studied to address different types of plastic wastes. For example, marine organisms may have evolved to degrade polymers in saline conditions and should provide insights into solutions regarding oceanic plastic pollution. The combination of physical and biological changes can influence efficiency, and the pre-treatment can improve plastics to increase surface area and the application of microbial enzymes. Genetic engineering is another tool for fabricating more effective and strong enzyme-producing microorganisms.

In conclusion, the biodegradation of plastic polymers by bacteria and fungi and the advancements in enzyme extraction and application provide great promise for combating plastic pollution. Further research efforts are necessary to continue exploring and improving microbial enzymes in order to realize their full potential as a sustainable solution for environmental protection. The combined strategies of improvement in enzyme efficiency, exploration of novel sources, and combination with physical approaches will help advance the field of plastic biodegradation further.

## 8. Conclusion

Plastics pose significant environmental hazards if poorly managed. Biodegradation by bacteria and fungi offers a promising solution, as many microbes produce enzymes that depolymerize polymers into

monomers, which can be repurposed into new products. This approach reduces environmental risks while providing sustainable enzyme sources. Synergistic strategies combining physical and biological modifications can enhance efficiency while exploring enzymes from diverse sources, such as plants, marine organisms, and microorganisms, which will improve environmental sustainability. Tailored approaches are needed to address the distinct biodegradation mechanisms required for different polymers, including engineering enzymes to target multiple polymers or enabling precise enzyme-polymer interactions. Future efforts should focus on genetically engineering enzymes for improved efficiency, stability, and specificity. Novel enzymes from extreme environments, such as deep-sea or thermophilic habitats, could address current challenges. Combining enzymatic degradation with pre-treatments like chemical or thermal processes may further accelerate plastic breakdown. For industrial use, key steps include scaling enzyme production through cost-effective fermentation methods and developing bioreactors for enzymatic plastic degradation. Integrating these systems into recycling facilities, alongside collaborations among academia, industry, and policymakers, can advance sustainable practices and reduce the environmental impact of plastic waste.

## CRediT authorship contribution statement

**Vishnu Suresh:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Rafeeya Shams:** Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kshirod Kumar Dash:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ayaz Mukarram Shaikh:** Visualization, Validation, Resources, Funding acquisition, Methodology, Software, Writing – review & editing. **Kovács Béla:** Visualization, Validation, Resources, Funding acquisition, Project administration, Software, Writing – review & editing.

## Consent to participate

Informed consent was obtained from all individual participants included in the study.

## Ethics approval consent

Not applicable.

## Availability of data and materials

The datasets generated and analyzed during this study are available from the corresponding author on reasonable request.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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